

# LONG RANGE CORRELATIONS AND RELATIVITY: METATHEORETIC CONSIDERATIONS

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Action-at-a-distance is a generic property of physical theories. As such, it is not a fruitful idea in theory building. Its absence confers a rigidity on a theory which we exemplify through analysis of long-range correlations of the EPR-type in relativistic theories. Rigidity is desirable for fundamental theories, and theory building should focus on structurally unstable properties, making action-at-a-distance a side issue. Though apparent superluminal effects seem to be present in many present-day physical theories, we maintain that they are not a basis for action-at-a-distance.

## 1. Introduction

Ever since the famous EPR debate [1, 2], there has been widespread speculations that long range quantum correlations are indication of some sort of action-at-a-distance. The situation is extremely subtle and the presence or absence of action-at-a-distance depends a lot on philosophical concerns [3], though many physicist would deny this. We do not want to enter this debate. The purpose of this essay is to expound the consequences of the existence of these correlations, in the peculiar way that they manifest themselves, concerning possible physical theories. Whether these theories are to be of an action-at-a-distance type or not, is something that depends on the details, interpretations, and conceptual content of the theories. The information we shall convey is to a large extent independent of all this, and so must be heeded by all interested in this debate.

## 2. Metatheory of Superluminal Communication

Although the light cone has been considered an impenetrable barrier, much of present-day physics, based on this impenetrability, actually predicts a variety of

phenomena that seem to bridge the gap between the subluminal and superluminal. Even plain classical Maxwell electrodynamics has superluminal solutions [4]. Quantum gravity effects allow for light to propagate outside the gravitational “light cone” calling into question just what is the exact causal structure of space-time [5]. Extremely general quantum field theoretic considerations seem to imply superluminal influences [6]. These examples can be multiplied many-fold. Effects seem to slip across the light cone in spite of a firm theoretic resolve to contain them. This fact alone is remarkable given the wide variety of theories for which this happens, and some general characteristic, unsuspected up to now, could probably be discovered to explain it. In any case, one need not be surprised that a widespread debate continues. A good portion of this debate seems to exist on the fringe of main-stream physics, in obscure journals and on the internet, and one should ask why.

What is needed of course is some way of proceeding without entering the details of particular theories. Superluminal situations arise out of details. What is not clear is their effect on life as we live it. Is it action-at-a-distance? This depends on many conceptual subtleties. Can one send a message? This is more straightforward. Can I hold a conversation with my relative on a Mars colony with each remark followed immediately by a response as in a normal living-room conversation, not suffering the usual speed-of-light time delay? Will we both agree, upon meeting each other two years later, that each one indeed said what the other remembered? These are uncontestable gross effects. This is much like machinery, wheels turning, lights flashing, and bar-room shouting. What one needs to establish is whether the superluminal effects implicit in present-day main-stream physics can have this “gross thermodynamic quality” or are they just peculiar properties of the theoretical apparatus which do not lead to the gross effects that are needed. The firm belief, almost faith, on part of the majority of “working physicists” that the second alternative is the truth, contributes to keeping a portion of this debate mostly on the fringe. The situation has not been helped by an abundance of arguments based on a faulty or partial understanding of modern physics and that are then easily if not trivially put down, often accompanied by vehement arguments by the proponent that this was not done. In a way this is reminiscent of the abundance in centuries past of proposals for perpetual motion, before a true understanding of thermodynamics was achieved.

Nick Herbert [7] for instance proposed an arrangement that would duplicate a photon state through stimulated emission. Superluminal communication is then easily achieved. This proposal quickly provoked various rebuttals [8, 9, 10] to the effect that no linear state transformer can clone a quantum state, an instance of the so called “No Cloning Theorem”. Stimulated emission simply does not work the way the proponent assumed it does, an assumption that implied non-linearities in

quantum mechanics of a type never observed.

The argument that in the EPR situation no superluminal communication is possible [11, 12, 13, 14] is that the statistical behavior of any detector placed on one arm of an EPR apparatus is completely independent of what is done on the other arm. Thus even though action-at-a-distance may be present as part of the “hidden gears of nature” that do indeed spin on the microscopic scale, our access to these processes, it is claimed, is such that we cannot create gross quality effects. Some dispute this last claim, but none have yet built a working device. In what way should the EPR situation be considered action-at-a-distance even though no energy or matter is transferred in any way, is to be left to the philosophically inclined [3]. We do not wish to deny the value of philosophical analysis, but call attention to the fact that the action-at-a-distance debate has forced upon us a level of philosophical subtlety usually absent in physical discourse. One does not need to enter such realms as much can still be done with more directly physical considerations.

Superluminal communication and action-at-a-distance are not logically equivalent, but of course closely related. The hidden-gears-of-nature position shows that one could maintain action-at-a-distance without producing gross quality effects, but discounting direct transfer of information to the receiver’s mind (and only in certain theories of the mind at that), it’s hard to see how one can receive a distant signal without the sender “acting” upon a physical entity that manifests the signal. The scientific merit of a hidden-gears-of-nature posture is dubious, and by action-at-a-distance we shall mean a gross quality one, and so we treat action-at-a-distance and superluminal communication as being about the same thing.

One cannot discount relativity. If we simply deny universality of special relativity then the debate becomes fruitless as no new guiding principle is brought forth to substitute the supremely powerful one that was discarded. As a local (space-time tangent-plane) symmetry, special relativity has been borne out with great precision. One cannot furthermore discount cosmology, as gross quality superluminal effects would surely, one expects, have profound effects on the structure of the universe.

One could suppose that relativity is not universally valid, and that there is a privileged frame, roughly, for instance, that of isotropic background cosmic radiation or that of isotropic galactic red-shifts, which is sensed by some processes and with respect to which instantaneous action-at-a-distance is possible. Any such theory would have no causality problems, would alleviate some of the paradoxical features of the abundant apparent superluminal effects, and could probably be stretched to fit the known facts, but conceptually and fundamentally would be very different from the current one. In the end a theory must be judged by experiment. Until then one should inquire if the tension resulting from stretching it to fit the facts is greater or not than the one in the current theory.

To make some headway into this complicated business, one can, instead of searching for theories that allow action-at-a-distance and then stretching them to make them hang on the known physical facts, take the inverse approach. Postulate a principle that disallows gross quality action-at-a-distance effects, something akin to the second law of thermodynamics, and see what this means for possible physical theories.

A useful notion is that of theory space. Consider all possible physical theories, or to be less vague, all possible physical theories of a given type. One can conceive of a type of topology on this space given by proximity of predicted results. To dispel some of the aetherial quality of this, consider a large set of descriptions of experimental arrangements, each with a finite number of possible outcomes. A theory is then a function that associates to each description the probability distributions of the outcomes. The set of all such functions is then the theory space, and the topology may well be the weak topology, that is, one for which a neighborhood is defined by proximity of the prediction of probability of a finite number of events. This approach is very akin to the “empirical logic” approach pioneered by Foulis and Randall [15]. Many questions concerning the space of theories can be precisely formulated and investigated in this manner.

Present day physical theory is a point in this space. It is surrounded by theories that are proximate in experimental predictions but that may well be radically different in other aspects. One is interested mainly in a weak neighborhood of the present-day theory as any serious alternative theory must agree with well-established results predicted by the present-day theory. The relevant concept now is that of structural stability. Do all neighboring theories share a property of the present-day theory or not? If not, how big, in an appropriate sense, is the set of neighboring theories that do? One has to work with some technical notion of “almost all”. Topologically this could be “dense” or “second category”. We say a property is structurally unstable if almost all theories in a neighborhood violate it, and structurally stable if almost all share it. Structural instability, in spite of this weak-sounding designation, is a sign of a strong fundamental theory as one then has sufficient reason to differentiate it from neighboring ones.

What emerges from metatheoretic studies is strong evidence toward the claim that, first of all, Lorentz covariance, the existence of self-subsisting physical states, and the existence of enough EPR-type long-range correlations, practically characterize present-day linear quantum theory, and second, that the absence of gross quality superluminal effects is structurally unstable, that is, almost all theories in the neighborhood of present day physics allow superluminal communication. The first hypothesis almost certainly can be replaced by general covariance of general relativity, the other two will be explained in the course of this essay. The struc-

tural instability explains many facts. One is a sociological one. Why is there an abundance of proposals of superluminal signaling devices based on present-day physics? First of all, the abundance of apparent superluminal effects in a variety of physical theories, pointed out at the beginning, means that many will stumble upon at least one of them, and so be induced to believe that such a device may be possible. Second, the slightest misunderstanding of present-day physics, or the slightest miscalculation within it, places one at a neighboring theory and then it's practically inevitable that one will conclude that superluminal communication is *really* possible. The argument may seem watertight as the most subtlest of errors will be enough to lead to the conclusion. Another fact is the great robustness of present-day theories. Serious alternatives seem to run up against insurmountable difficulties. Thus Weinberg's non-linear quantum theory was abandoned by its creator exactly because he could not formulate a relativistic version [16]. One now understands why he failed.

What do we mean by "self-subsisting physical states"? In quantum theory (in the Schrödinger picture), a physical state evolves deterministically by a unitary group in Hilbert space. Such a state is generally created at some time and destroyed later in a measurement process, but the deterministic evolution can be extended to both temporal infinities. In particular it can be extended to a time before its creation, which means it could have been created at an earlier time and in some other place. Likewise the evolution can be extended to a time after its destruction, which means it could have been subjected to measurement at a later time and in different place. The state is thus an autonomous physical entity having no memory of its birth nor any prescience of its demise. Regardless of the ontological status of such entities, physical theories use them as algorithmic devices to compute joint probabilities of observed events. A sequence of events is then seen as the interaction of a state with a measurement apparatus (or something akin to it) by which the state is modified and then evolves until the next interaction when it suffers another modification followed by another evolution, and so on. Thus joint probabilities of events are computed using the interpolating existence of evolving self-subsisting entities. This is not a logically necessary picture. One can take the strange sounding position that physical states are not really necessary to do physics, as one can conceive of ways of calculating joint probabilities without the use of such interpolating entities. In fact certain patterns of probabilities cannot be interpreted this way. The "consistent histories" approach to quantum mechanics [18, 19] in fact abolishes to a large extent the reliance on self-subsisting physical states and can easily produce examples [18] where joint probabilities cannot be explained by such. Such an approach also suggests [17] that the obstruction to relativistic non-linear quantum mechanics, so lamented by Weinberg [16], can be overcome.

To begin our analysis [20], we work with the hypothesis that there may be some physical processes that do not conform to usual quantum mechanics but that these only take place in very particular situations, whereas for the vast majority of other situations, such as experiments done up to now, any deviation from normal quantum mechanical predictions is imperceptible. One could thus posit a photon cloner that acts in a non-linear fashion, and that it can take part in an experiment in which normal quantum mechanics is adequate for processes not involving it. Explicitly one assumes that, in any given inertial frame, up to the use of an unconventional device, the usual quantum mechanical reasoning can be used, including the projection rule. Up to such a moment, ordinary quantum mechanics determines what the physical state is. At the point of using the unconventional device one of course must explicitly say what would happen (a photon would be cloned in the above cited example).

What one succeeds in showing under these hypotheses is that certain types of deviations, specifically non-linearities and lack of true randomness of outcomes, allow for superluminal signals. This makes ordinary quantum mechanics a structurally unstable theory in relation to the property of not allowing superluminal communication. This is important as many proponents of modifications to ordinary quantum mechanics are in fact implicitly assuming our hypotheses and so face a real risk of coming into conflict with relativity, assuming the existence of superluminal communication is such a conflict.

More explicitly, [20] shows that, given our hypotheses, 1) in a Hilbert space of dimension at least three, any state transformer, including temporal evolution, must be given by a linear transformation of density matrices, 2) if a state transformer takes pure states into pure states and has at least two states in its range, it can be implemented either by a linear or an anti-linear operator, and 3) randomness of possible outcomes in one experiment implies randomness of outcomes in all.

It must be emphasized, as was mentioned before, that the above assumptions are about formalism and not about interpretation. What is postulated is an altered formalism associated to what is generally known as the Copenhagen interpretation, but no interpretational hypotheses are made. State collapse is used, but no assumption as to its ontological nature is made, only that it's a legitimate calculating device for joint probabilities. What the results say is that joint probabilities cannot be calculated by certain rules if superluminal communication is to be ruled out.

It should also be noted that part of our understanding about the standard formalism is that it's capable of giving account of a relativistically covariant theory. This is not straightforwardly obvious given the instantaneous nature of wave function collapse [21, 22], but this does not preclude lorentz covariance of observable quantities. What the standard formalism lacks is thus *manifest* covariance while being able to provide for covariance of measurable magnitudes. It's precisely this

fact that makes the theory structurally unstable, for a perturbation in the formalism is likely to make the manifest non-covariance capable of producing real effects, such as superluminal communication. In fact all theories that incorporate any frame-dependent notions, such as *temporal* evolution, and which have no gross quality superluminal effect can probably be interpreted as a “hidden gears of nature” theory. A small change in the theory can expose the hidden gears and make them accessible to our manipulation and so superluminal communication becomes possible. A recipe for constructing a superluminal signaling device is generally very easy to discover in any such modified theory, for instance, Gisin [23] has done it explicitly for Weinberg’s non-linear quantum mechanics.

There is also an argument that relates the absence of gross quality superluminal effects and the second law of thermodynamics showing that under certain hypotheses, which include special relativity, superluminal communication can be used to foil the second law of thermodynamics. This is because with superluminal communication, information can flow backward in time. One can then foresee details of normal thermodynamic fluctuations and take advantage of them to extract work from heat. This points out the thermodynamic character of any action-at-a-distance proposal within special relativity, a connection that was also pointed out by Elitzur [24].

A striking feature of the above conclusions is their generality. This in fact throws doubt on the emphasis given to superluminal communication and makes one suspect a more fundamental tension in alternate theories. In fact, the presence of superluminal signals as they emerge from the analysis, *per se* already contradicts relativity. Consider a superluminal signaling device making use of the “exposed” state-collapse mechanism and that is to operate between two distant locations in the reference frame of two observers at relative rest. According to the general results, if the first observer invokes the signaling process, then the second observer will, after a negligible time interval, detect it. We can say that for the second observer the *onset* of the signal is practically simultaneous with the initiating event. Onset is a physical event and so all observers ought to agree where in space-time it occurred. Consider how the same situation is seen in a reference frame of a moving observer. He would see a different initial state, find that his physics is described by possibly different deviant equations, but, assuming relativity, he does all his reckoning in relation to *his* plane of simultaneity. The argument that leads to superluminal signals is sufficiently general that the moving observer will also expect these to exist, but now in relation to his plane of simultaneity, and so he would expect the onset of the signal along the second observer’s world-line to be significantly different from what was determined before. Since onset is an uncontestable physical fact, this is a contradiction. The sheer generality of the results leads us to seek a more fundamental viewpoint from which lack of superluminal communication would be

a consequence and not a hypothesis, much as one supplants thermodynamics with statistical mechanics and derives the second law from more basic principles.

The above problem arises because of the dubious mixture of special relativity with self-subsisting physical states that undergo change in measurement situations. Consider a measurement with space-like separated instrumental events such as a correlation measurement of the EPR type. In one frame the measurements on the two parts are simultaneous and so can be considered as just parts of a single measurement, while in another frame the two measurements are successive with intervening time evolution. These two descriptions must be equivalent and produce the same observable results. Thus relativity imposes constraints that relate the measurement process to the evolution. These constraints are structurally unstable and neighboring theories are almost all inconsistent with relativity.

In another study [25], we explore the nature of these constraints in a relativistic quantum logic framework. This was already presaged in [20] where it was found that the absence of gross quality superluminal effects can be used as supporting argument for assuming certain axioms in the foundations of quantum mechanics thus suggesting that quantum mechanics owes some of its aspects to space-time structure.

Without going into the details, the axiomatic approach posits a system of propositions concerning outcomes of experiments performed in regions of space-time subject to (beyond some standard quantum-logical impositions) four crucial ingredients: 1) Lorentz covariance, 2) state transformation due to measurements, taking pure states into pure states, 3) causality, and 4) something called “covariance of objectivity”. The second ingredient is an appropriate generalization of the projection postulate, the so called “collapse of the wave function”. Depending only on the state and the measurement arrangement, it incorporates the basic idea of self-subsisting physical states as interpolating entities used in calculating joint probabilities of experimental outcomes. The third ingredient posits that experimental arrangements in space-like separated regions are compatible in the technical sense of quantum logic, a generalization of the commutativity of observables in standard quantum theory. The fourth ingredient is a technical elaboration of Lorentz covariance that is needed due to the presence of the self-subsisting physical states, as these are frame dependent entities (they interpolate measurement events in a temporal sequence, which can be frame dependent). What the postulate basically means is that if one observer identifies a mixed state as arising from a measurement process in his causal past with unknown outcomes, and attributes to it a decomposition into pure components on the basis of objective correlations, then another such observer would make the same attributions using the appropriate Lorentz transformed objects.

What results from this analysis is that the joint probabilities of outcomes from



space-like separated experiments must satisfy an explicit constraint. This constraint already precludes the use of long range correlations for superluminal communications, along the same line of reasoning as in standard quantum mechanics, but this not too surprising as one has strong causality ingredients in the axioms. What is more interesting is that if these constraints were to be extended to measurement situation which are no longer space-like but which are still performed with compatible instruments, then one could deduce the famous “covering law” of Piron’s axiomatic quantum theory [26], from which a Hilbert space model (not necessarily with a complex base field) for the proposition system follows.

It seems at first hand that there is no way to bridge the barrier between the space-like and time-like compatible arrangements. The presence of enough long-range correlations however can do it. Suppose you want to study right-hand circularly polarized photons. One way is to simply put an appropriate filter in front of a light source and those photons that get through are of the right kind and so can be observed at will. Another equivalent way is to set up an EPR-type arrangement that creates singlet two-photon states with the individual photons flying off in opposite directions. Put now the same filter on the *distant* arm of the EPR apparatus and *nothing* on the near arm. Observe at will. Half of the photons observed are right-hand circularly polarized and half are in the orthogonal left-hand circularly polarized state, and as the measurements are done, there is no way of knowing which is which. If all one wants however is analysis of experimental outcomes, this is no problem, just wait enough time that the results (passage through the filter or not) at the distant arm of each photon pair are available (typical correlation experiment situation) and simply throw out all the experimental data for the instances where the distant photon did not pass through the filter. This provides you with data now of just the right-hand circularly polarized photons at the near arm. The fact that these two experimental procedures are equivalent is a feature of ordinary quantum mechanics and depends on the existence of a particular entangled state, the two-photon singlet.

In the general axiomatic analysis, if one postulates an analogous equivalence principle, that to any time-like experimental arrangement with compatible instruments, there is an equivalent space-like arrangement performed on an appropriate long-range correlated states, then one completes the argument toward the covering law and a Hilbert space model of quantum mechanics.

Instead of being simple inconsequential curiosities, as some have maintained, long-range correlations may be instrumental in making physics what it is. They provide the link between space-time structure and mechanics and a bridge between the superluminal and the subluminal. Why such a bridge should exist cannot be answered at this level of analysis. A more appropriate scenario would probably be

quantum gravity, where the light cone, and consequently the distinction between superluminal and subluminal, are emergent concepts and don't exist at the fundamental level. Apparently the physically relevant solutions for our universe are such that gross quality superluminal situations are suppressed. This should emerge as a feature of such a theory and not a fundamental ingredient, much as quark confinement is a feature of certain gauge theories.

### 3. Conclusions

What can be conclude from all of the above considerations? In the first place, it's remarkable, as was mentioned in the beginning, that apparent superluminal effects have been pointed out in such a wide variety of theories that ostensibly are relativistic and causal. This cannot be a coincidence and some general characteristic must be at work. A theory of any complexity about space-time situations may just easily contain logical implications between propositions concerning situations in space-like separated regions, which then may be *perceived* as having to do with gross quality superluminal effects. A superluminally propagating classical solution of Maxwell's equations [4], certainly seems to be a harbinger of such effects. These perceptions are clearly part of what is happening, but it probably is not the full story, and the situation certainly bears further study.

If gross quality superluminal effects are found experimentally, this most likely would radically transform our ideas about the world. Experiments should of course be performed, but the question then is where to search for these effects. The above mentioned apparent superluminal situations in existing theories seems a natural start, but the situation seems so general that it's hard to imagine that some of these are just apparent and others truly lead to gross quality situations. If all are capable of producing gross quality effects, it's strange that no irrefutable experimental evidence has up to now been forthcoming. It's also unlikely that causal physics is a mathematical inconsistency. The sheer generality of the situations argues against them. In the end it seem likely that all these effects are apparent and any experimental attempt based on them to be frustrated.

Another conclusions is that action-at-a-distance is a "soft", that is, a structurally stable concept. In any formalization of the space of all theories it would be characterized by a set of inequalities (the presence of a non-zero effect) which would be maintained by any small change in the theory. As such it's present in almost any theory one can devise. By the same token, perception of its possibility in almost any type of theory should be widespread. Its absence is a structurally unstable concept. Fundamental theories that are to be taken seriously should be structurally unstable in relation to its fundamental characterizing properties. Otherwise there would not be sufficient reason to distinguish them from any neighboring theory. Weinberg [16]

argues repeatedly and eloquently for the importance of theory rigidity and in this we agree with him.

Taking this into account, advocacy of action-at-a-distance, is *per se* basically counterproductive. It does not point us to a new fundamental theory. It may be that a new fundamental theory that supplants the present one would have action-at-a-distance as one of its features, but the new theory would not be characterized by this, but by a new rigid set of properties.

## References

1. Einstein, A., Podolsky, B. and Rosen, N., *Physical Review*, **47**, 777 (1935).
2. Bohr, N. *Physical Review*, **48**, 696 (1935).
3. d’Espagnat, B. *Foundations of Physics*, **11**, 205 (1981).
4. Rodrigues, W. A. Jr. and Maiorino, J. E. physics/9710030 and references therein.
5. Konstantinov, M. Yu. gr-qc/9810019 and references therein.
6. Hegerfeldt, G. C. quant-ph/9809030 and references therein.
7. Herbert, N., *Foundations of Physics*, **12**, 1171 (1982).
8. Dieks, D., *Physics Letters A*, **92**, 271 (1982).
9. Milonni, P. W. and Hardies, M. L., *Physics Letters A*, **92**, 321 (1982).
10. Wootters, W. K. and Zurek, W. H., *Nature*, **299**, 802 (1982).
11. Eberhard, P. H., *Nuovo Cimento B*, **38**, 75 (1977).
12. Eberhard, P. H., *Nuovo Cimento B*, **46**, 392 (1978).
13. Ghirardi, G. C. and Weber, T., *Lettere Nuovo Cimento*, **26**, 599 (1979).
14. Ghirardi, G. C., Rimini, A. and Weber, T., *Lettere Nuovo Cimento*, **27**, 293 (1980).
15. There is a vast literature concerning this, which space does not allow us to cite here. See for instance Foulis, D. J. *Journal of Natural Geometry*, **13**, 1, (1998) and references therein.
16. Weinberg, S., *Dreams of a Final Theory*, Vintage Books (1992). See pp. 88–89 for the discussion on the failure of relativistic nonlinear quantum theory.
17. Svetlichny, G. “On Relativistic Non-linear Quantum Mechanics” in M. Shkil, A. Nikitin, V. Boyko, eds, *Proceedings of the Second International Conference “Symmetry in Nonlinear Mathematical Physics. Memorial Prof. W. Fushchych Conference”*, Institute of Mathematics of the National Academy of Sciences of Ukraine, Kyiv, 1997.
18. Hartle, J. B., “Spacetime Quantum Mechanics and the Quantum Mechanics of Spacetime”, in *1992 Les Houches Ecole d’été, Gravitation et Quantifications*
19. Omnès, R., *The Interpretation of Quantum Mechanics*, Princeton University Press, (1994)
20. Svetlichny, G., *Foundations of Physics*, **28**, 131, (1998).
21. Aharonov, Y. and Albert, D., *Physical Review D*, **24**, 359 (1981).
22. Aharonov, Y. and Albert, D., *Physical Review D*, **29**, 228 (1984).
23. Gisin, N., *Physics Letters A*, **143**, 1 (1990).
24. Elitzur, A. C., *Physics Letters A*, **167**, 335 (1992).
25. Svetlichny, G. “Lorentz Covariance and the Covering Law”, pre-print MAT.15/95, Mathematics Department, Pontificia Universidade Católica of Rio de Janeiro. To appear in a revised version in 1999.
26. Piron, C., *Foundations of Quantum Physics*, W. A. Benjamin, Inc., London (1976).